Flavor changing scalar couplings and $t\gamma(Z)$ production at hadron colliders

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Abstract

We calculate the contributions of the flavor changing scalar (FCS) couplings arised from topcolor-assisted technicolor ($TC2$) models at tree-level to the $t\gamma$ and tZ production at the Tevatron and LHC experiments. We find that the production cross sections are very small at the Tevatron with $\sqrt{s} = 1.96TeV$, which is smaller than 5 fb in most of the parameter space of $TC2$ models. However, the virtual effects of the FCS couplings on the $t\gamma(Z)$ production can be easily detected at the LHC with $\sqrt{s} = 14TeV$ via the final state $\gamma l\bar{\nu}b$ ($l^+l^-l\bar{\nu}b$).

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I. Introduction

The top quark, with a mass of the order of the electroweak symmetry breaking($EWSB$) scale $m_t \approx 178.0 \pm 4.36 GeV$[1], is singled out to play a key role in probing the new physics beyond the standard model(SM). The properties of the top quark could reveal information regarding flavor physics, $EWSB$ mechanism, as well as new physics beyond the SM[2]. Hadron colliders, such as the Tevatron and the $CERN\ LHC$, can be seen as top quark factories. One of the primary goals for the Tevatron and the LHC is to accurately determine the top quark properties, and to see whether any hint of non-standard physics may be visible.

The anomalous top quark couplings tqv (q = c-or u-quarks and $v = \gamma$, Z, or g gauge bosons), which are arise from the flavor changing (FC) interactions, can affect top production and decay at high energy collider as well as precisely measured quantities with virtual top contributions. In the SM, this type of couplings vanish at the tree-level but can be generated at the one-loop level. However, they are suppressed by the GIM mechanism, which can not be detected in the present and near future high energy experiments[3]. Thus, any signal indicating this type of couplings is evidence of new physics beyond the SM and will shed more light on flavor physics in the top quark sector.

Single top quark production is very sensitive to the anomalous top coupling tqv, which can be generated in supersymmetery, topcolor scenario, and other specific models beyond the SM. Thus, studying the contributions of this type of couplings to single top production is of special interest. This fact has lead to many studies involving single top production via the tqv couplings in lepton colliders[4,5] and hadron colliders[6,7,8].

To completely avoid the problems arising from the elementary Higgs field in the SM, various kinds of dynamical $EWSB$ models have been proposed, and among which the top-color scenario is attractive because it can explain the large top quark mass and provide possible $EWSB$ mechanism[9]. Almost all of this kind of models propose that the scale of the gauge groups should be flavor non-universal. When one writes the non-universal interactions in the mass eigen-basis, it can induce the tree-level FC couplings. For example, the top-pions $\pi_t^{\pm,0}$ predicted by topcolor scenario have large Yukawa couplings

to the third family quarks and can induce the tree-level flavor changing scalar (FCS) couplings[10], which have significant contributions to the anomalous top couplings tqv[5]. The aim of this paper is to calculate the contributions of the FCS coupling $\pi_t^0\bar{t}c$ to the processes $gc \rightarrow t\gamma$ and $gc \rightarrow tZ$ in the framework of topcolor-assisted technicolor (TC2) models[11], and see whether the effects of the FCS coupling $\pi_t^0\bar{t}c$ on $t\gamma$ and tZ production can be detected at the Tevatron and the LHC experiments.

II. The calculations of $t\gamma(Z)$ production in $TC2$ models

For $TC2$ models[9,11], the underlying interactions, topcolor interactions, are assumed to be chiral critically strong at the scale about $1TeV$ and coupled preferentially to the third generation, and therefore do not possess GIM mechanism. This is an essential feature of this kind of models due to the need to single out top quark for condensate. The non-universal gauge interactions result in the mass eigen-basis, which can induce the anomalous top quark couplings tuv and tcv. However, the tuv couplings can be neglected because the FCS coupling $\pi_t^0\bar{t}u$ is very small[10]. The effective forms of the anomalous coupling vertices Λ_{tcZ}, $\Lambda_{tc\gamma}$, and Λ_{tcg} can be writted as[5]:

$$\Lambda^{\mu}_{tcZ} = ie[\gamma^{\mu}(F_{1Z} + F_{2Z}\gamma^5) + p_t^{\mu}(F_{3Z} + F_{4Z}\gamma^5) + p_c^{\mu}(F_{5Z} + F_{6Z}\gamma^5)], \tag{1}$$

$$\Lambda^{\mu}_{tc\gamma} = \Lambda^{\mu}_{tcZ}|_{F_{iZ}\rightarrow F_{i\gamma}}, \qquad \Lambda^{\mu}_{tcg} = ig_s\frac{\lambda^a}{2}[\gamma^{\mu}F_{1g} + p_t^{\mu}F_{2g} + p_c^{\mu}F_{3g}] \tag{2}$$

with

$$F_{i\gamma} = F_{iZ}|_{v_t=\frac{2}{3},a_t=0}, \qquad F_{ig} = \frac{3}{2}F_{i\gamma}. \tag{3}$$

Where λ^a is the Gell-Mann matrix. The from factors F_{iv} are expressed in terms of two - and three - point standard Feynman integrals[12]. The expressions of F_{iZ} are given in Ref.[5].

Obviously, the FCS coupling $\pi_t^0\bar{t}c$ can generate contributions to the processes $g(p_g) + c(p_c) \rightarrow t(p_t) + \gamma(p_\gamma)$ and $g(p_g) + c(p_c) \rightarrow t(p_t') + Z(p_Z)$ via the anomalous top quark couplings $tc\gamma$, tcZ, and tcg. The relevant Feynman diagrams are shown in Fig.1, in which Fig.1(a) and Fig.1(b) come from the anomalous $tc\gamma$ and tcZ couplings, while Fig.1(c) and Fig.1(d) come from the anomalous tcg coupling. The renormalized amplitudes for these

processes have similar forms with those of the process $\gamma p \to \gamma c \to t\gamma(Z)$, which have been given in Ref.[8].

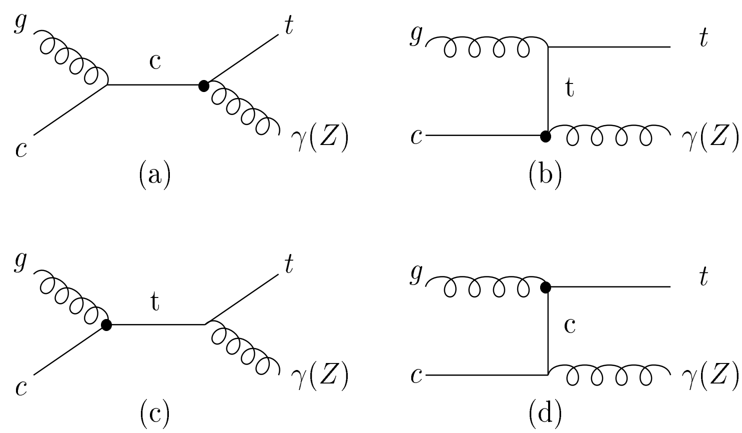

Figure 1: Feynman diagrams for $t\gamma(Z)$ production contributed by the anomalous top coupling vertices $\Lambda_{tc\gamma}, \Lambda_{tcZ}$, and Λ_{tcg}.

After calculating the partonic cross sections $\hat{\sigma}_i(\hat{s})$ for the subprocesses $gc \to t\gamma$ and $gc \to tZ$, the total cross sections $\sigma_i(s)$ at hadron coliders are obtained by convoluting $\hat{\sigma}_i(\hat{s})$ with the partion distribution functions $f_{c/p}(x_1, Q)$ and $f_{g/p}(x_2, Q)$ of the initial state particles c and g:

$$\sigma_i(s) = \int\int dx_1 dx_2 f_{c/p}(x_1, Q) f_{g/p}(x_2, Q) \hat{\sigma}_i(\hat{s}), \tag{4}$$

where $\hat{s} = xs$, and $x = x_1 x_2$. In our calculation, we will take the CTEQ5 parton distribution function for $f_{c/p}(x_1, Q)$ and $f_{g/p}(x_2, Q)$ with $Q^2 = \hat{s}$[13].

III. Numerical results and conclusions

From above equations, we can see that the cross sections of $t\gamma$ and tZ production at the Tevatron and the LHC are dependent on two free parameters ε and m_{π_t} of $TC2$ models, except the SM input parameters α_e, α_s, S_W, m_Z and m_t. In $TC2$ models, topcolor interactions make small contributions to $EWSB$ and give rise to the main part

of the top quark mass, $(1-\varepsilon)m_t$ with $0.01 \leq \varepsilon \leq 0.1$, a model dependent free parameter. The limits on the top-pion mass m_{π_t} may be obtained via studying its effects on various observables[9]. It has been shown that m_{π_t} is allowed to be in the range of a few hundred GeV depending on the models. As numerical estimation, we will assume m_{π_t} and ε in the ranges of $200GeV \sim 400GeV$ and $0.01 \sim 0.1$, respectively.

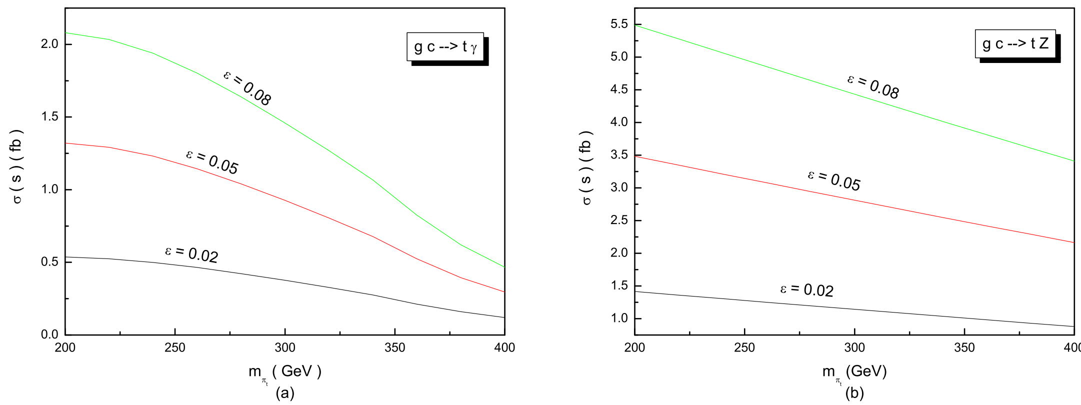

Figure 2: The cross section $\sigma(s)$ of $t\gamma(Z)$ production as a function of the top-pion mass m_{π_t} for three values of the parameter ε at the Tevatron with $\sqrt{s} = 1.96TeV$

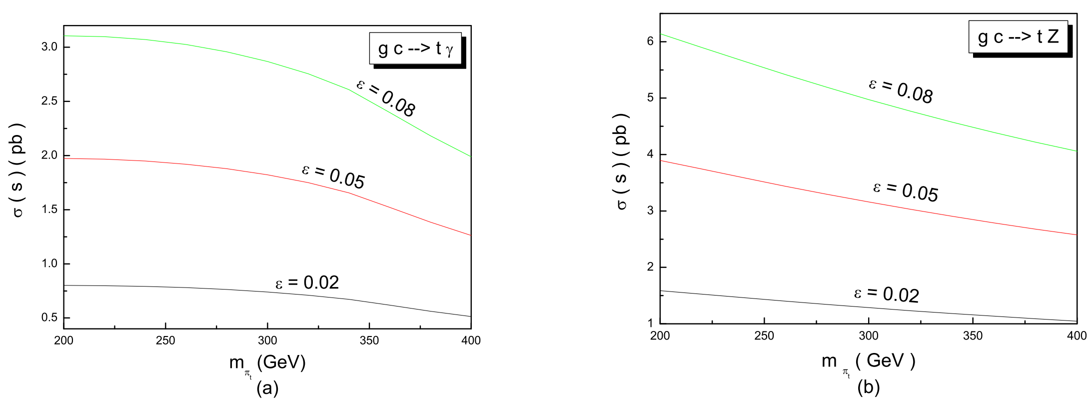

Figure 3: The cross section $\sigma(s)$ of $t\gamma(Z)$ production as a function of m_{π_t} for three values of the parameter ε at the LHC with $\sqrt{s} = 14TeV$

The cross sections $\sigma_i(s)$ of $t\gamma(Z)$ production at the Tevatron with $\sqrt{s} = 1.96TeV$ and LHC with $\sqrt{s} = 14TeV$ are plotted as functions of the neutral top-pion mass m_{π_t} for

three values of the free parameter ε in Fig.2 and Fig.3, respectively. From these figures, we can see that the $t\gamma$ production cross section is smaller than tZ production cross section at the same collider experiment. This is because the effective coupling strength of $\Lambda_{tc\gamma}$ is smaller than that of Λ_{tcZ} and the c. m. energy $\sqrt{s} \gg m_Z$. For $200GeV \leq m_{\pi_t} \leq 400GeV$ and $0.02 \leq \varepsilon \leq 0.08$, the cross sections of $t\gamma$ and tZ production at the Tevatron are in the ranges of $1.2 \times 10^{-4}pb \sim 2.1 \times 10^{-3}pb$ and $8.8 \times 10^{-4}pb \sim 5.4 \times 10^{-3}pb$, respectively. If we assume the yearly integrated luminosity $\pounds_{int} = 2fb^{-1}$ for the Tevatron with $\sqrt{s} = 1.96TeV$, then the number of the yearly production events is smaller than 10 in almost of all parameter space of $TC2$ models. Thus, it is very difficult to detect the effects of the FCS coupling $\pi_t^0\bar{t}c$ on the $t\gamma$ and tZ production at the Tevatron experiments. However, it is not this case for the future LHC experiment with $\sqrt{s} = 14TeV$ and $\pounds_{int} = 100fb^{-1}$. There will be $3.1 \times 10^5 \sim 5.1 \times 10^4$ $t\gamma$ events and $6.1 \times 10^5 \sim 1.0 \times 10^5$ tZ events to be generated per year.

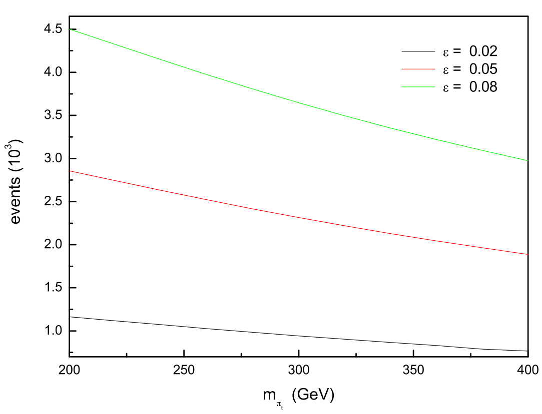

Figure 4: The number of the $l^+l^-l\bar{\nu}b$ events generated at the LHC with $\sqrt{s} = 14TeV$ is showed as a function of m_{π_t} for three values of the parameter ε

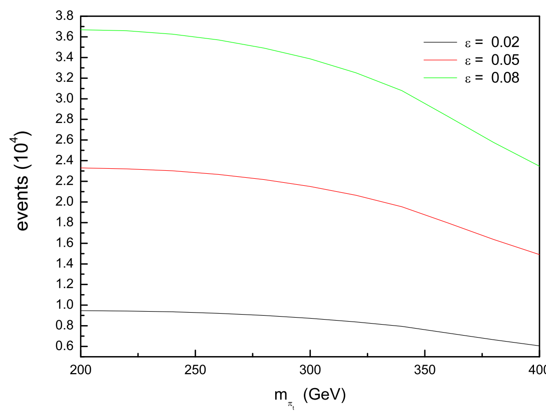

Figure 5: The number of the $\gamma l\bar{\nu}b$ events generated at the LHC with $\sqrt{s} = 14TeV$ is showed as a function of m_{π_t} for three values of the parameter ε

In general tZ production gives the possible observable five fermion final states with at least one b quark $ffffb$ including $\nu\bar{\nu}jjb$ with $Z \to \nu\bar{\nu}$ and $W \to q\bar{q'}$, $jjl\nu b$ with $Z \to q\bar{q'}$ and $W \to l\bar{\nu}$, etc. It has been shown that the final state $\nu\bar{\nu}jjb$ with branching ratio $B_r(tZ \to \nu\bar{\nu}jjb) \approx 13\%$ is the best signal event for detection the new physics effects

on tZ production at the Tevatron with $\sqrt{s} = 1.96TeV$ and $\pounds_{int} = 2fb^{-1}$[14]. Although the final states $b\bar{b}l\bar{\nu}b$ and $l^+l^-l\bar{\nu}b$ have smaller branching ratios $B_r(tZ \rightarrow b\bar{b}l\bar{\nu}b) \approx 3.3\%$ and $B_r(tZ \rightarrow l^+l^-l\bar{\nu}b) \approx 1.5\%$, they are the most interesting modes at the LHC with $\sqrt{s} = 14TeV$ and $\pounds_{int} = 100fb^{-1}$, due to smaller backgrounds. In Fig.4, we plot the number of the signal event $l^+l^-l\bar{\nu}b$ at the LHC as a function of m_{π_t} for three values of the free parameter ε. In this figure, we have taken the experimental efficiency ϵ for detection the final state fermions as the commonly used reference values: $\epsilon = 95\%$ for leptons and $\epsilon = 60\%$ for b quark. One can see from Fig.4 that, in most of the parameter space of $TC2$ models, there will be several hundreds and up to thousands observed $l^+l^-l\bar{\nu}b$ events to be generated at the LHC experiments. Thus, the virtual effects of the FCS coupling $\pi_t^0\bar{t}c$ on tZ production should be detected in the future LHC experiments.

Compared with those of tZ production, the final states with a photon and three fermions of $t\gamma$ production are very simply, only $\gamma l\bar{\nu}b$ and γjjb depending whether the SM gauge boson W decays into leptons or hadrons. The leptonic final state $\gamma l\bar{\nu}b$ has a branching ratio $B_r(t\gamma \rightarrow \gamma l\bar{\nu}b) \approx 21.8\%$ and the hadronic final state γjjb has a branching ratio $B_r(t\gamma \rightarrow \gamma jjb) \approx 67.8\%$. The $\gamma l\bar{\nu}b$ final state is the most interesting signal event, due to its small γWj background[14]. The number of the observed $\gamma l\bar{\nu}b$ events is plotted in Fig.5 as a function of m_{π_t} for three values of the parameter ε. One can see from Fig.5 that the number of the observed $\gamma l\bar{\nu}b$ events are larger than that of the observed $l^+l^-l\bar{\nu}b$ events for tZ production in all of the parameter space. So, the FCS coupling $\pi_t^0\bar{t}c$ can be more easy detected via the $t\gamma$ production process than via the tZ production at the LHC experiments.

$TC2$ models also predict the existence of the neutral scalar top-Higgs h_t^0, which is a $t\bar{t}$ bound and analogous to the σ particle in low energy QCD. Similar to the neutral top-pion π_t^0, it can also give rise to the large effective $tc\gamma$ and tcZ couplings via the FCS coupling $h_t^0\bar{t}c$. Our explicit calculation shows that the effect of the FCS coupling $h_t^0\bar{t}c$ on the $t\gamma(Z)$ production is similar to that of the FCS coupling $\pi_t^0\bar{t}c$.

In many of the extensions of the SM, the GIM mechanism does not work so well as in the SM. The top quark FC interactions might be predicted in supersymmetery, topcolor

scenaric, and other specific models beyond the SM, which can generate significantly contributions to rare top decays and single top production processes[2,15]. Thus, these interactions can lead to observable effects in various high energy colliders[16]. For example, the large anomalous top couplings tcv generated by the tree-level FCS couplings $\pi_t^0\bar{t}c$ or $h_t^0\bar{t}c$ can enhance the branching ratios of the rare top decays $t \rightarrow cv$[17] and the cross sections of single top production at high energy e^+e^- collider(LC)[5] and the ep colliders[8]. In the context of $TC2$ models, the FCS couplings $\pi_t^0\bar{t}c$ and $h_t^0\bar{t}c$ make the cross section of the process $e^+e^- \rightarrow \bar{t}c$ in the range of $0.014fb \sim 0.35fb$ at the LC experiment with $\sqrt{s} = 500GeV$ and that of the process $ep \rightarrow \gamma c \rightarrow t\gamma(tZ)$ in the range of $0.14pb \sim 1.37pb(0.13pb \sim 1.35pb)$ at the $THERA$ collider with $\sqrt{s} = 1000GeV$, which may be detected in these future collider experiments. Furthermore, Ref.[17] has shown that, in most of the parameter space of $TC2$ models, there are $B_r(t \rightarrow c\gamma) \sim 1 \times 10^{-6}$, $B_r(t \rightarrow cZ) \sim 1 \times 10^{-4}$ and $B_r(t \rightarrow cg) \sim 1 \times 10^{-4}$. At the LHC experiment with $\sqrt{s} = 14TeV$ and $\pounds_{int} = 100fb^{-1}$, the production cross section of the top quark pairs via standard QCD interactions is about $8 \times 10^5 fb$. If we assume that the top quark decays via $t \rightarrow cv$ with $Z \rightarrow e^+e^-$ and the antitop quark decays via $\bar{t} \rightarrow W^-\bar{b}$ with $W^- \rightarrow l^-\bar{\nu}_l$, then, at most, there are several hundreds observable events to be generated per year. Thus, the virtual effects of the FCS couplings $\pi_t^0\bar{t}c$ or $h_t^0\bar{t}c$ can be more easy detected via the $t\gamma(Z)$ production process than via the rare top decays $t \rightarrow cv$ at the LHC experiments.

Topcolor scenario is one of the important candidates for the mechanism of $EWSB$. A key feature of this kind of models is that topclor interactions are assumed to couple preferentially to the third generation and there do not posses GIM mechanism. The non-universal gauge interactions can induce the FCS couplings $\pi_t^0\bar{t}c$ and $h_t^0\bar{t}c$. If the virtual effects of the FCS couplings can indeed be detected at the LHC experiments, it will be helpful to test topcolor scenario and understand $EWSB$ mechanism.

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